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Ground-Based Simulations of ISS Exercise Countermeasures at NASA Glenn Research Centers Exercise Countermeasures Laboratory – Compliant Interface Dynamics Using a Floating Treadmill

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The enhanced Zero-gravity Locomotion Simulator (eZLS) at NASA Glenn Research Center is currently being utilized to investigate the dynamics of walking and running on a compliant treadmill surface to study the effects on musculoskeletal health as well as verify the performance of the vibration isolation system being developed for the second treadmill (T2) to be used on the International Space Station (ISS). This is particularly important to Astronaut exercise prescriptions for bone health since the exercise equipment on the International Space Station is required to provide isolation to minimize the loads transmitted to the ISS structure. The consequence of locomotion on a compliant interface is that the peak ground reaction forces important to bone density maintenance are significantly reduced. To counteract these detrimental effects, adjustments to exercise prescriptions must be made to provide and adequate level of Daily Load Stimulus (DLS) to the body. To facilitate this work, the eZLS is capable of providing from 1 to 3 degrees of freedom (DOF) and variable compliance and mass to simulate the walking and running conditions on a vibration isolated treadmill aboard the ISS.

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Nomenclature

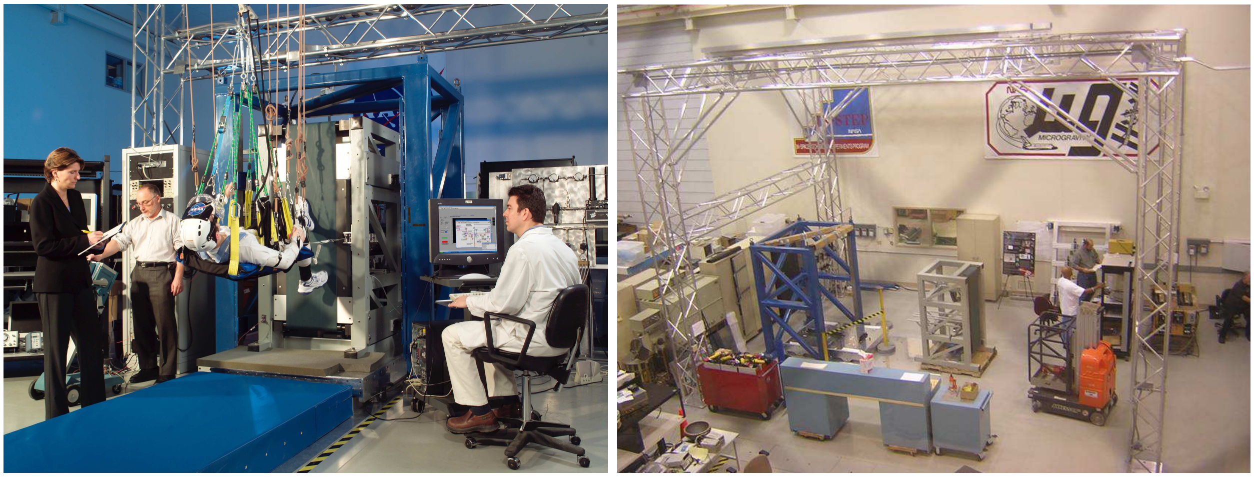
cm	centimeter
F	force
G	Earth Gravity ($9.81m/s^2$)
Hz	Hertz (cycles per second)
kg	kilogram
kN	kilonewton
lbs	pounds
m	meter
mph	miles per hour
N	Newton
s	second
t	time
x	displacement vector
BW	body weight
DLS	Daily Load Stimulus
DOF	degrees of freedom
ECL	Exercise Countermeasures Lab
$eZLS$	enhanced Zero-gravity Locomotion Simulator
GRC	Glenn Research Center
GRF	Ground Reaction Force
$ISPR$	International Standard Payload Rack
ISS	International Space Station
JSC	Johnson Space Center
$NSBRI$	National Space Biomedical Research Institute
SBS	Series Bungee System
SLD	subject load device
$sZLS$	Stand-alone Zero-gravity Locomotion Simulator
$T2$	ISS Second Treadmill
$UTMB$	University of Texas Medical Branch
VIS	vibration isolation system
ZLS	Zero-gravity Locomotion Simulator

I. Introduction

The enhanced Zero-gravity Locomotion Simulator (eZLS) at NASA Glenn Research Center (GRC) was developed and implemented with collaborative efforts from NASA GRC, NASA Johnson Space Center (JSC), The Cleveland Clinic, and ZIN Technologies and is shown in Figure 1. This system expanded and enhanced the capabilities of its predecessor, the Zero-gravity locomotion simulator (ZLS)[1,2] located at The Cleveland Clinic. The usefulness and success of these systems as important ground-based, partial-g analog test beds also led to the development of the Stand-alone Zero-gravity Locomotion Simulator (sZLS) (3-D CAD rendering shown in Figure 2) currently housed in the General Clinical Research Center Satellite Flight Analog Research Unit at the University of Texas Medical Branch at Galveston under the technical direction of NASA JSC.

All three systems utilize a supine suspension system to counteract the gravity load on the subject and feature several methods for imparting various simulated gravity loads to the subject (commonly referred to as the subject load device or, SLD) through the use of bungees or linear motors on the eZLS and sZLS and bungees or a Pneumatic Subject Load Device (P-SLD) on the ZLS. Additional specific details about these systems has been published elsewhere[1–7] and need not be reiterated here.

Both the ZLS and sZLS have rigid, grounded reaction frames that the treadmill is fixed to. The eZLS, however, features a floating treadmill rack that can be coupled to the rigid reaction frame by means of springs and dampers (isolators) to provide a customizable, compliant interface for the study of exercise countermeasures and their effectiveness in providing suitable mechanical loading to maintain musculoskeletal health. This is especially useful as a spaceflight analog since the exercise equipment on the ISS must be



(a) eZLS with subject suspended.

(b) Overhead view of eZLS to illustrate the relative scale of its components.

Figure 1. The eZLS Treadmill in the Exercise Countermeasures Lab at NASA Glenn Research Center.

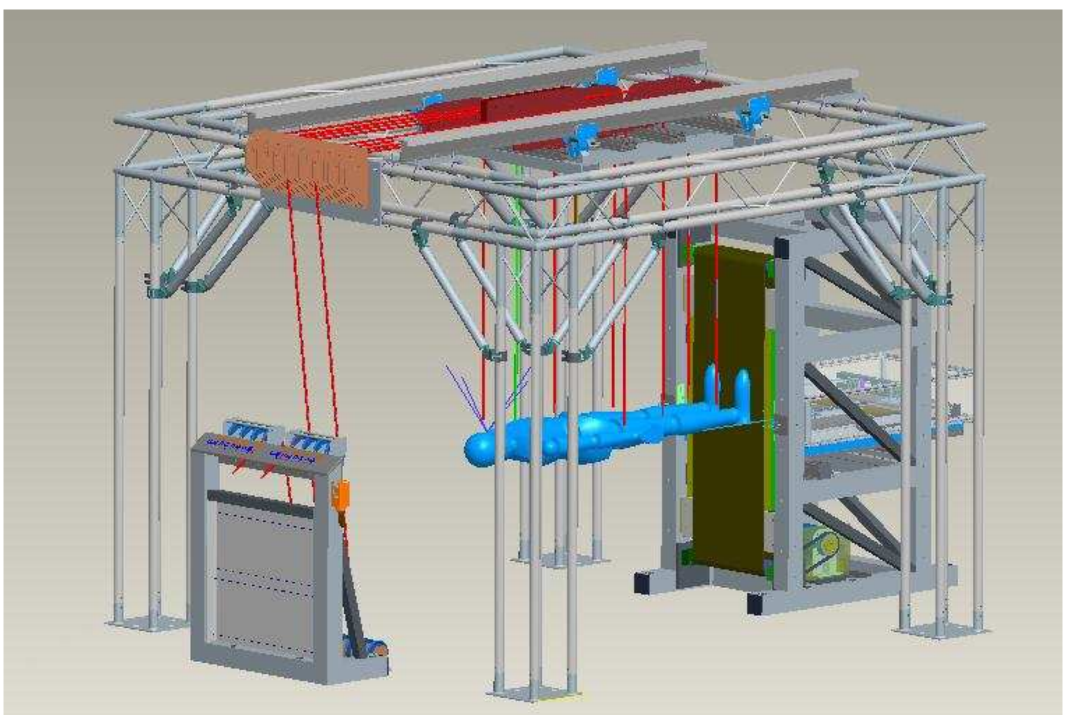
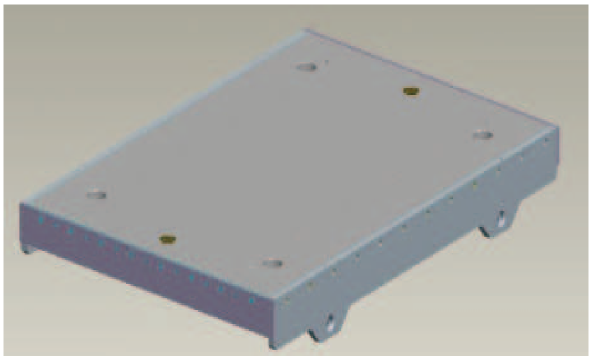


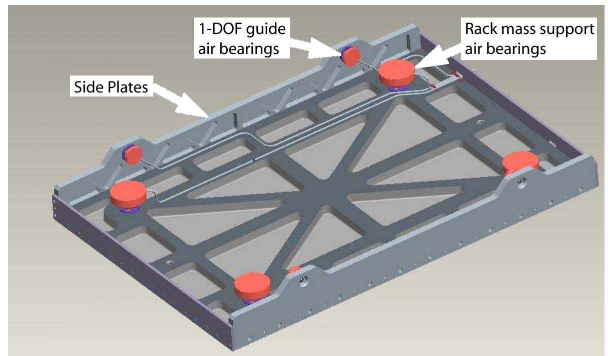
Figure 2. 3D CAD rendering of the sZLS Treadmill.

dynamically isolated from the main ISS structure to mitigate crew induced exercise forces and vibrations from being transmitted to the ISS structure.

The eZLS treadmill rack can be floated on four air bearings to support its vertical load as shown in the CAD rendering in Figure 3(b). When energized, the air bearings provide a near frictionless interface to allow the treadmill rack to translate freely. The side plates with the air bearings, also shown in Figure 3(b) guide the treadmill rack for 1-DOF motion. These side plates and air bearings can be removed to allow two or three DOF, depending on the isolator constraints. The 2-DOF configuration provides translation in a plane while the 3-DOF configuration allows plane translation plus rotation about an axis perpendicular to the translation plane.



(a) Top side of air bearing table.



(b) Under side of air bearing table.

Figure 3. eZLS air bearing table to support the treadmill rack.

An unfortunate consequence of a vibration isolated treadmill is that even imparting a simulated 100% body weight (BW) load to the crew member through the SLD does not produce the same ground reaction force (GRF) experienced during $1 - G$ terrestrial locomotion. The result is insufficient mechanical loading to maintain healthy bone density during extended stays on spaceflight missions. Research has shown that astronauts lose, on average, $1 - 2\%$ of their bone mineral density (BMD) per month and the condition can persist after rehabilitation upon return to Earth.[8, 9]

To date, little work has been done to investigate the effects of locomotion on compliant surfaces as it pertains to bone maintenance and sufficient exercise prescriptions for crew members to maintain a healthy status for long duration missions. In addition to the magnitude of the GRF, recent studies have suggested that the rate of change of force with respect to time (dF/dt) also influences bone maintenance and thus the efficacy of exercise countermeasures.[10–12]

II. eZLS Compliant Treadmill Rack Interface

The eZLS treadmill can currently be configured for up to 3-DOF. The vibrated isolated treadmills used on the ISS have 6-DOF so that forces generated from any direction are attenuated. Figure 4 shows the conventions used when describing translation and rotation of the treadmill surface. The eZLS floating rack can be configured for heave and sway translation as well as roll rotation.

A. One Degree of Freedom Configuration

A recent study conducted utilized the eZLS in the 1-DOF heave configuration to specifically investigate GRF at three different compliances. This work will help to form a basis for the effects of locomotion on a compliant surface, be used to develop and verify computational models and provide a framework for dictating sufficient DLS when exercising on a vibration isolated platform.

The purpose of the research study was to ultimately develop a new type of effective exercise program, using a zero gravity simulator and a harness that would be acceptable to astronauts during prolonged space flight. This research was sponsored by the National Space Biomedical Research Institute (NSBRI) and was performed at the Lerner Research Institute in the Department of Biomedical Engineering on the

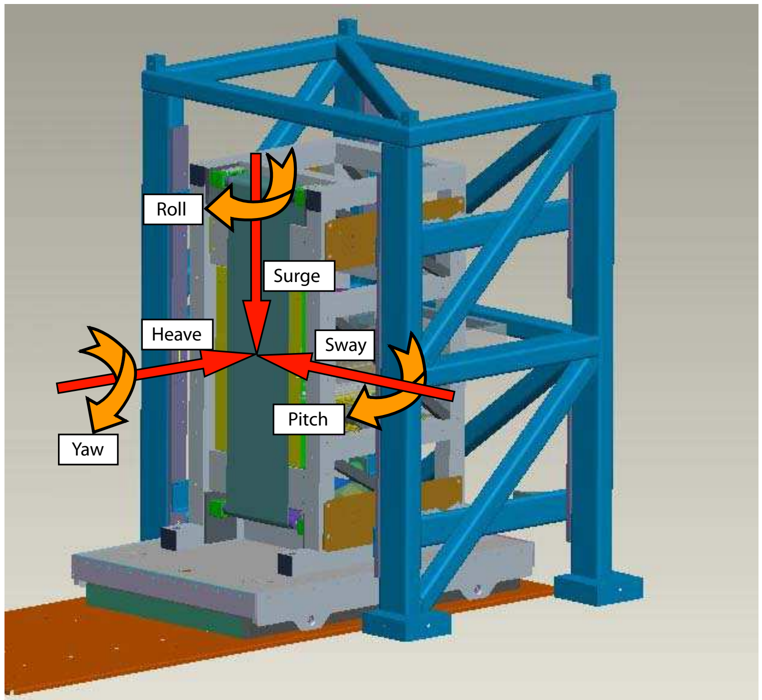
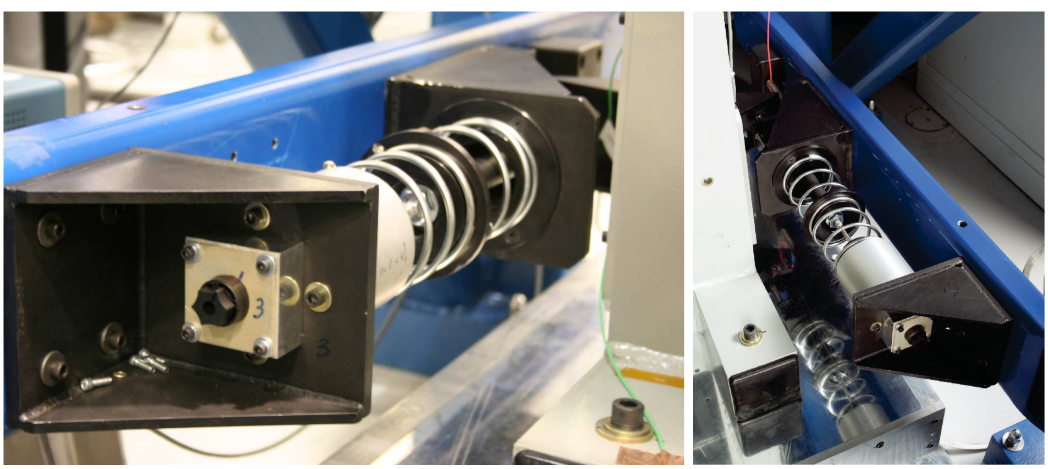


Figure 4. Illustration of naming conventions used to describe the DOF of a compliant treadmill.



(a) (b)

Figure 5. Isolator assemblies used in $1 - DOF$ compliant study.

main campus of the Cleveland Clinic Foundation and at the NASA Glenn Research Center in the Exercise Countermeasures Lab (ECL).

The eZLS floating treadmill rack was coupled to the rigid reaction frame with four spring and damper assemblies as shown in Figure 5. These assemblies can be configured to provide a different stiffness, damping and natural frequency by changing the springs and adjusting the orifice on the dampers. Load cells are mounted between the isolators and the reaction frame to directly measure the dynamic force transmitted to the reaction frame by exercising subject. Accelerometers are mounted to the floating treadmill rack to provide additional inputs to develop and verify the computational model. The mass of the floating treadmill rack during this series of trials was 635 kg.

A total of four treadmill rack configurations were used during this the study. These were the hard mount case and three isolator stiffness values to produce compliances that are approximately an order of magnitude apart. Detailed analysis is currently in progress but early estimates of the transfer functions with apparent compliance values are given in Figure 6 for each case.

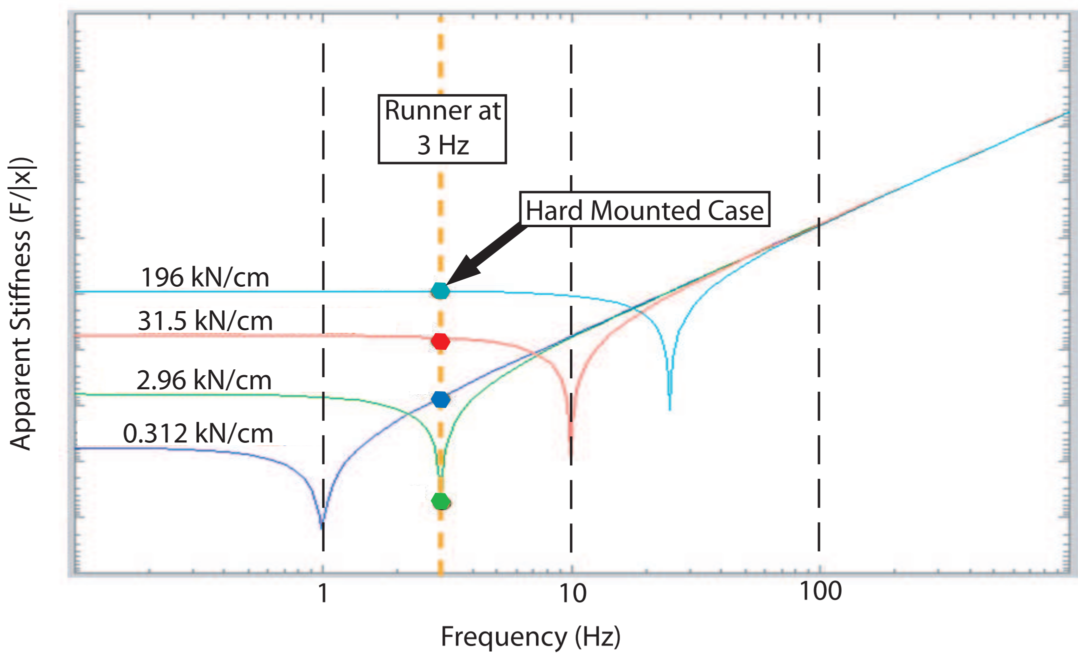


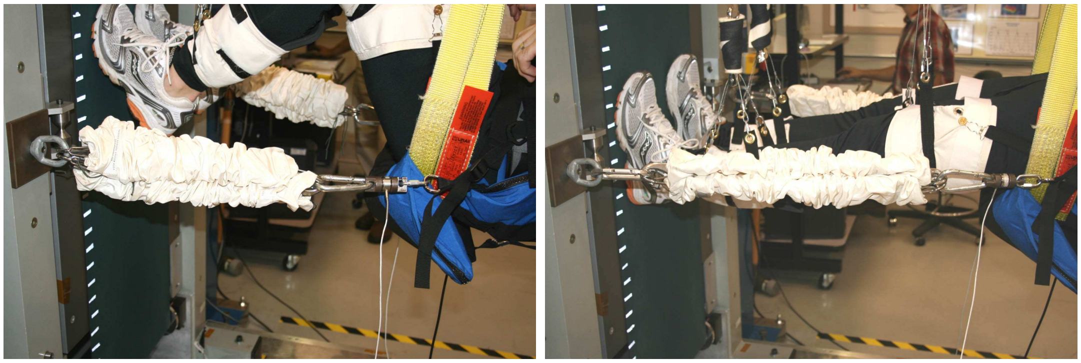
Figure 6. eZLS compliance characterization.

The SLD employed in this study was the Series Bungee System (SBS) which was developed for use in ISS exercise countermeasures and is shown in Figure 7. The SBS bungees interface between the subject exercise harness and eye bolts fastened to the rack on each side of the treadmill. The load setting is adjustable by adding or removing carabiners to change the initial length of the SBS bungee assembly. The SBS bungees have a stiffness of 5.25 to 7 N/cm in their operational range though as part of this study, the SBS bungees' mechanical properties were measured statically and dynamically to provide accurate inputs to the computational model.

B. Three Degree of Freedom Configuration

Work currently in progress on the eZLS is testing and verification of a new isolator design being developed for the new T2 treadmill for the ISS. The T2 will be housed in a modified International Standard Payload Rack (ISPR) and the entire rack and treadmill assembly will be interfaced to the main ISS structure through passive isolator assemblies. This work is being supported by the Wyle Life Sciences Group and Bastion Technologies, Inc. in collaboration with ZIN Technologies and NASA GRC.

For this investigation, the eZLS has the side plate air bearings removed to provide heave and sway translation and roll rotation. An additional interface structure was added to the floating rack and rigid reaction



(a) SBS relaxed.

(b) SBS loaded.

Figure 7. Series Bungee System (SBS)

frame of the eZLS to accommodate 6 isolator assemblies and partially simulate the planned configuration for the T2 VIS. Figure 8 shows the isolators installed on the eZLS. Additional mass was also added to the eZLS floating rack to bring the mass up to 1000 kg (the anticipated mass of the T2 system) and align the center of gravity of the eZLS with the T2.

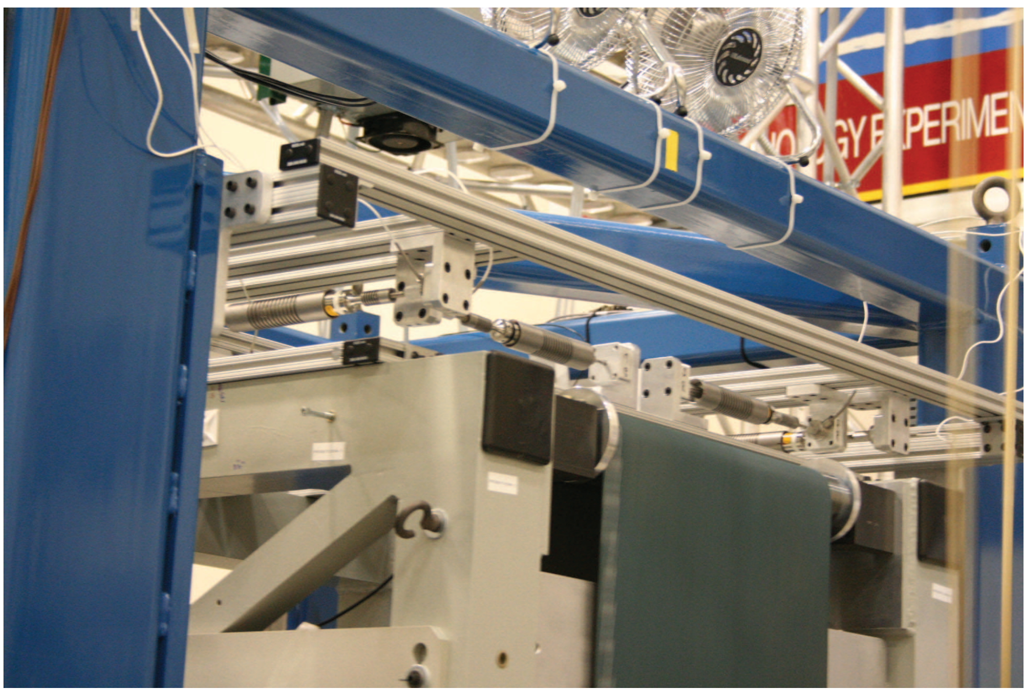


Figure 8. T2 isolators installed on the eZLS.

III. Preliminary Results

Detailed analysis and interpretation of the results from the recent tests is ongoing and little conclusions have been reached thus far. Figure 9 is provided for comparison purposes and shows one cycle of locomotion for each of the four cases from the 1-DOF study along with the 3-DOF case from the T2 testing. Each of the plots shown in Figure 9 is data from the same subject. The data from the 1-DOF study is at a treadmill speed of 6 mph, and 100% BW loading. The data from the T2 testing is at 5 mph and 90% BW loading.

Figure 10 shows only the GRF peaks from the force plate data for each of the 1-DOF complaint cases.

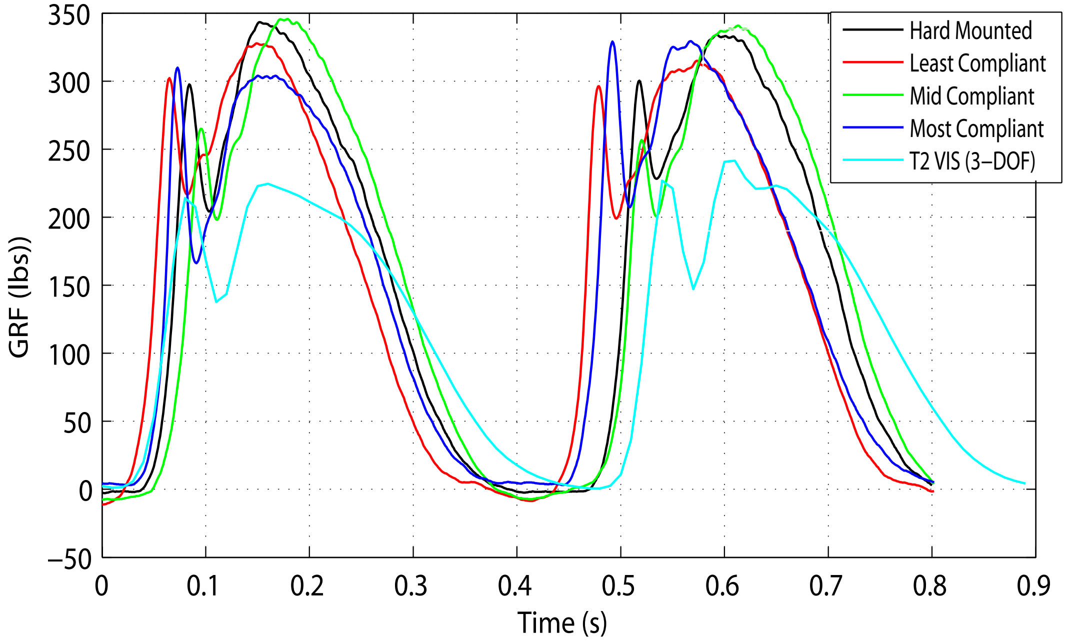


Figure 9. GRF from each of the compliant cases presented.

The algorithm essentially pick out the heel strikes and toe-offs during running. From the magnitude and distribution of this data it can be seen that not only the compliant nature of the interface has an effect on GRF magnitude and shape but also the frequency characteristics of the system. Depending on the resonant frequencies present, it is possible for the subject and the system to be at different phases such that at certain times during the same trial, the GRF can vary significantly.

IV. Computational Modelling

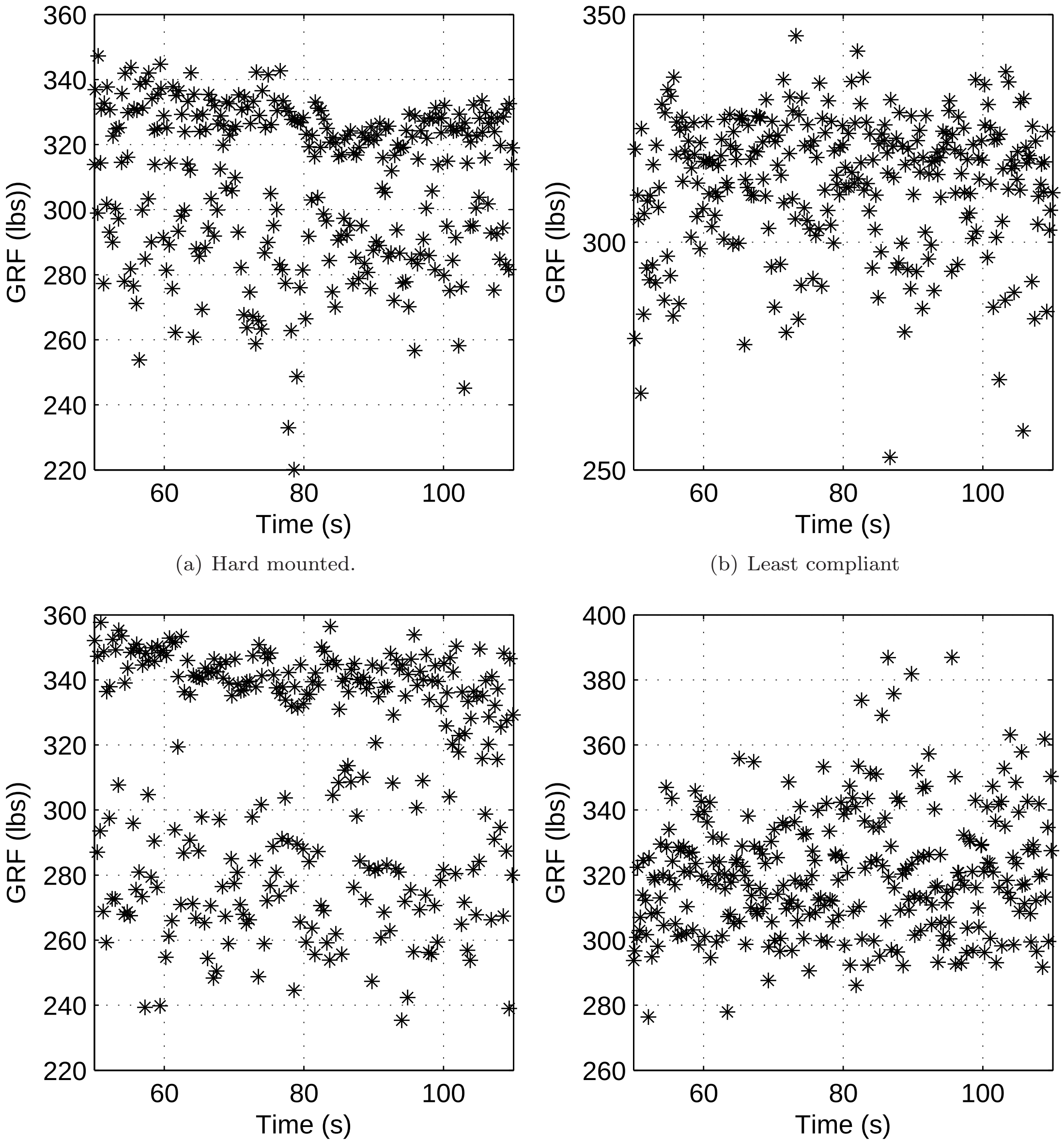
To provide additional tools to help predict compliant interface dynamics, a model is being developed that incorporates the runner-treadmill interface dynamics (including the SLD) as well as the treadmill to ground interface dynamics as illustrated in Figure 11.

Models of the eZLS and runner dynamics have been developed in MATLAB/Simulink in phases as shown in Figure 12. Using data from the NSBRI study, the models are currently being verified and refined. The compliance of the eZLS running surface has the characteristics of a mass-spring-damper system; spring elements dominate the low frequency compliance with mass dominating the high frequency compliance.

V. Conclusion

The dynamics of locomotion on a multi-DOF interface represent a complex system especially when attempting to develop a robust model that accounts for the variability in human biomechanics. A wide range of studies need to be conducted under a variety of conditions to have a sufficient statistical basis to incorporate all the constituents accurately. As can be observed in Figures 9 and 10, the differences for the 1-DOF cases are subtle and detailed analysis is required to make decisive conclusions. What is more obvious is that the 3-DOF interface significantly reduces the GRF (Figure 9) even when accounting for the 10% reduced SLD load.

Given that, with current exercise equipment and prescriptions, astronauts are still losing bone mass on space flight missions, a better understanding of the biomechanics and physiology needs to be obtained to maintain crew health. To this end, research and development in this area must be ongoing in order to support future planned long duration missions in the interest of crew health and their ability to perform at expected levels safely.



(a) Hard mounted.

(b) Least compliant

(c) Mid compliant.

(d) Most compliant

Figure 10. GRF peaks from the 1-DOF study. Subject BW = 175 lbs, 100% BW loading, 6 mph.

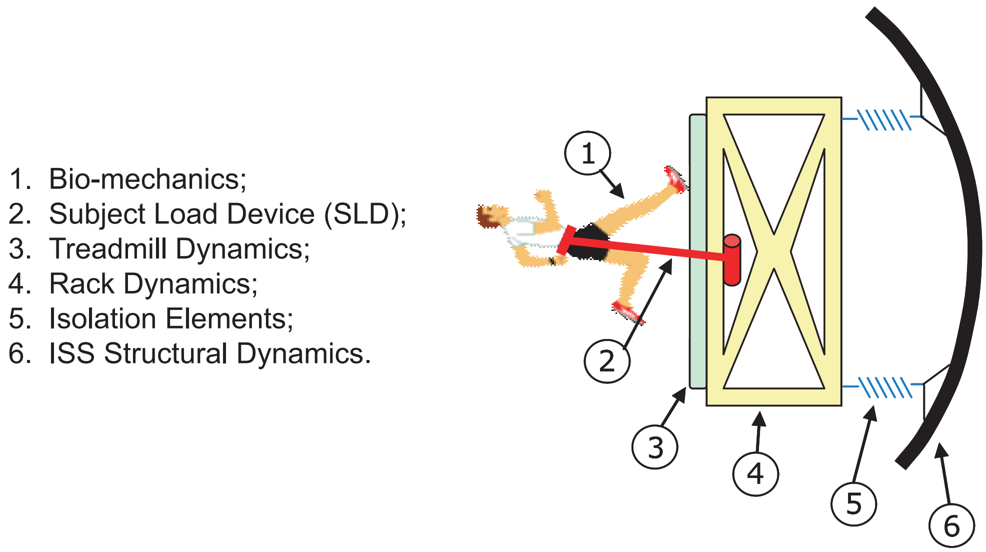


Figure 11. Pictorial showing the isolated treadmill interface dynamics to be considered.

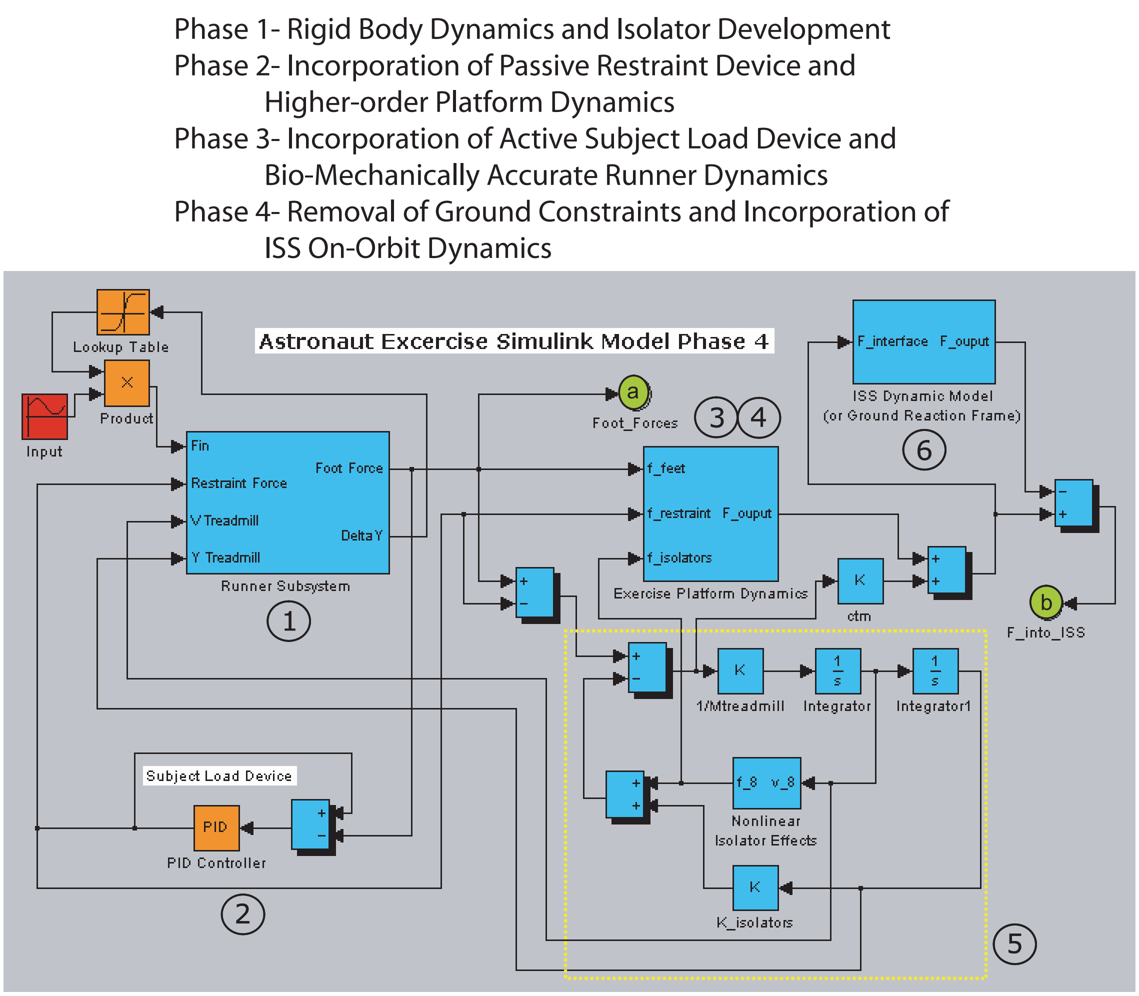


Figure 12. Block Diagram depicting the MATLAB/Simulink being developed to describe runner dynamics on a vibration isolated exercise platform.

VI. Acknowledgements

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